System Architecture for Guided Herd of Robots Exploring Titan[1,2,3]

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Abstract — This paper describes a system architecture for an aerobot blimp guiding and controlling a herd of sondes on Titan's surface. Options for inertial navigation are proposed that make use of a direct communication link to Earth. A potential field controller is used for autonomous tracking of terrain features on the surface, and hazard avoidance. The result of distributed simulation studies demonstrate that the method used for control is feasible even if significant uncertainty exists in the dynamics and environmental models.

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1. INTRODUCTION

We address the problem of how to achieve the autonomous operation of a herd of cooperating vehicles deployed in unknown planetary environments (Titan, Mars, Venus) for in-situ sampling and data collection. This idea is a valid candidate for all future Planetary Exploration missions targeting scientific returns in such areas of surface geology and tropospheric or stratospheric sampling. A herd or flock of mobile sensors is deployed in a totally unknown and unexpected environment, and must be easily reconfigured or repositioned to a more favorable location (providing more scientific throughput, better coverage, etc). Figure 1 depicts an artist's rendition of Titan blimp delivering one member of the herd to the moon's surface.

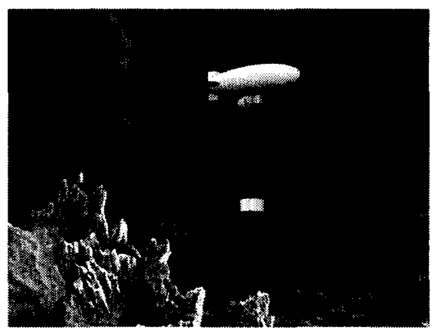

Figure 1. Artist's rendition of Titan blimp delivering one member of the herd to the moon's surface.

A herd leader (blimp) is identified, and the rest of the herd of mobile vehicles autonomously tracks the commands of the leader. We propose a potential field approach for autonomous command and control, and a centralized estimation scheme for intra-herd range determination. Inertial knowledge is acquired via land radio beacons and via Direct to Earth communication. The blimp and surface sondes redistribute appropriately despite the uncertain environment. Numerical results show the performance and robustness of the algorithms in the distributed simulation testbed we have developed at JPL for this application, and

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[2] IEEEAC paper #1581
[3] This research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

shows the promise of the approach for future missions of this type.

2. COOPERATION ARCHITECTURE

Multiple robots offer excellent opportunity for distributed scientific data collection. Efficient collection of distributed science information requires deploying many sensor packages/units in different locations. These locations may be characterized by hazards such as active vents/ice flows, floating ice masses, unpredictable local environmental flows or terrain features, different illumination conditions. The objective of the concept being described in this paper is to demonstrate active cooperative control of herds of mobile sondes in Titan's environment to increase autonomy and direct herd towards a common goal. Controlling cooperative sensor herds is a critical technology for autonomous planetary sampling.

Our approach is to develop algorithms/techniques for cooperative, distributed sensing and control of multiple sondes in Titan's environment, and to demonstrate our concept in simulation. The objectives of the model development are: 1) to enable parametric studies; and 2) to conceive and test possible control options for herd trajectory & attitude control and for sample capture scenario. This was accomplished by a progressive build-up of models of increasing complexity, namely: 1) first order models, 2) quick order-of-magnitude determinations, 3) point mass, enabling ascent/descent and trajectory analysis, 4) few parameters, simple to handle, full six-degrees-of-freedom, enabling simulation studies, and 5) lots of parameters, difficult to handle, multibody models.

Multiple Robots are advantageous since they can : 1) Manage homogeneous vs. heterogeneous herd, 2) they have the capability to model other agents in herd, 3) they can interact via sensing (kin recognition), 4) they can interact via communication (network topology & comm. protocols), 5) or they can interact via the environment (cooperation without communication).

We define cooperation as follows: given a specific task (i.e. collect as much scientific data of interest, from as many locations as possible, and return sample to origin), a herd displays autonomous collaborative behavior if, due to some underlying mechanism of cooperation, there is a net increase in the total utility of the system. This involves: homogeneity/heterogeneity of vehicles, task decomposition, task allocation among members, fault-tolerance and hazard avoidance, distributed sensing and communication, possible inference of what other ones think, geometric aspect: non-intersecting path-planning, learning aspect and self-organized behavior, and possible conflict management The herd's objective is to accomplish a specific task, namely: to collect as much scientific data of interest, from as many locations as possible, and return sample to origin. In the case of Titan's exploration, the main goals are to explore the atmosphere in order to understand the climate and atmosphere composition of Titan, to explore the surface to understand the geophysics and mineralogy of Titan, and to collect and analyze a sample in-situ, and possibly return it to Earth.

Cooperation may be the result of genetically determined individual behavior (eusocial – insects), or may be the result of social interactions between selfish agents. In any case, representative cooperation architectures are: 1) Cellular roBOTics System, bioinspired, decentralized, 2) SWARM, distributed with large number of agents, 3) ALLIANCE, small to medium size heterogeneous teams. The learning process may be reinforcement-based, to adapt to changes in environment, with the goal of evolving flocking behavior, or to resolve resource conflict. Formal metrics for cooperation and system performance, and for grades of cooperation, are still missing.

Lack of effective sensors can render the cooperation paradigm very difficult to implement. Collective robotics must deal with all of the HW/SW problems of single-robotics systems, complicated by multiplicity factor. Use of GPS-like environment can compensate for limited vision of agents, but can place severe environmental constraints under which agents operate, because acoustic features of environment may interfere with GPS.

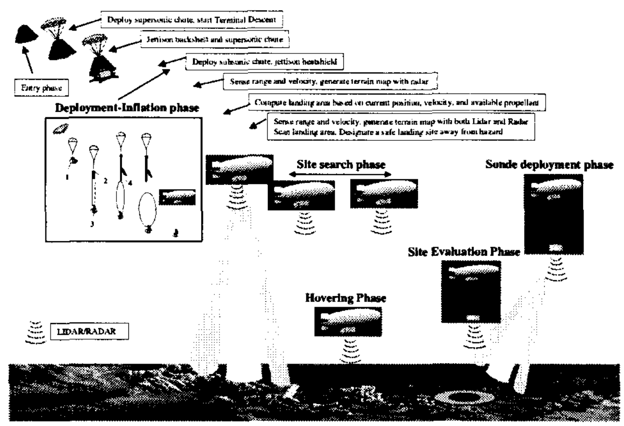

Figure 2. System Delivery Phases.

Some *qualitative* metrics for performance of Autonomous Robots are related with maintaining formation dynamics (deviation from template: % distance, % bearing), with the degree of independence of decision making for each element (limit no. of queries to centralized leader requesting commands for action), with the survivability of each element in unknown environment (successfully negotiate obstacles, communicate through obscurations), or with the capability of assuming leader role when needed (move from centralized to decentralized architecture).

The herd cooperation challenges that we have identified are: formation relative sensing and control, synchronous herd reconfiguration and reorientation, power optimality, centralized or decentralized distributed control and estimation, reliable actuation/sensing mechanisms, tolerant to environmental uncertainty, distributed communication, crosslinks, downlinks, high speed distributed computing, data management & autonomy, collaborative behavior, autonomous fault detection/recovery, coordinated instruments and science planning/processing, asynchronous processing.

3. System Delivery Phases

Figure 2 depicts the delivery phases of the blimp and herd formation.

The surface package with all associated systems is packed inside the aeroshell. After entering into the atmosphere the aftshell and the heatshield separate and the parachute deploys. Few seconds after reaching the terminal velocity the surface package container opens and the blimp deploys with the suspended inflation system and payload. Some moments after start of the inflation the parachute releases, and the blimp with the inflation system continue to descend. The inflation system is released when the inflation process is completed and the blimp and the parachute reach sufficient separation; the blimp starts to ascend to the float altitude. First, the blimp inflates in a vertical attitude, and then turns into a horizontal orientation while turning the engines on for stability. In this initial phase, several problems exist requiring new technology effort: 1) Shock alleviation mechanism needed to mitigate blimp envelope stresses during deployment; 2) Dynamic stability of blimp during inflation; 3) Does the blimp float safely while it is being inflated?

After the initial inflation phase, the Site Search Phase follows. In this phase, the blimp:

- Senses range and velocity, generates terrain map with radar
- Computes landing area based on current position, velocity, and available power
- Senses range and velocity, generates terrain map with both Lidar and Radar
- Scans landing area. Designates a safe landing site away from hazard

Next, the Site Evaluation Phase begins. This phase features: Site characterization, Hazard determination, Plan terminal approach; Prioritize the current vs. previous sites, Calibrate sensors to current location, Triangulate position, Plan next way points, Decide if terrain vs. pool must be negotiated, Estimate local winds and adapt trajectory.

During the Hovering Phase, the blimp performs: Site imaging, Hazard avoidance, Execute terminal approach, Do science, Sonde Path Planning, Sonde Power Planning/Allocation, Decide if sondes will/will not be deployed, Blimp touches down and anchor, Download previous data batch to Earth/orbiter.

Finally, the Sonde Deployment Phase is characterized by:

- Tether deployment and retrieval
- Touch-down to deploy sondes
- Deploy buoyant depot which then delivers sondes
- Anchor to ground, then deliver sondes
- Maintain local inertial knowledge during deployment
- Ensure power to sondes is available
- Do science on retrieved samples
- Talk to orbiter/Earth for download

Figures 3 and 4 depict the sonde deployment and retrieval sequence, as well as the types of communication occurring during these operations. One or more sondes deploy from an intermediate buoyant platform, and can remain tethered to it or be released into the environment.

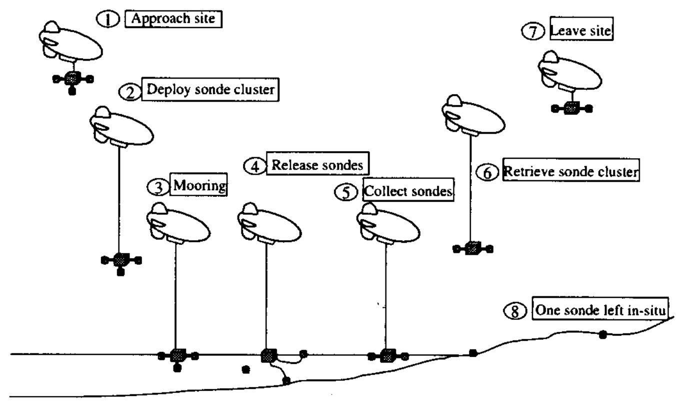

Figure 3. Sonde Deployment Phases from Blimp.

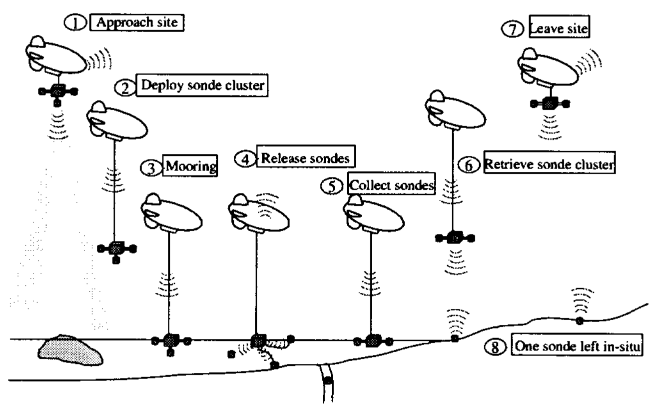

Figure 4. Sonde-Blimp Cooperation Scenario.

4. Inertial Navigation

In general, three options exist to enable blimp surface navigation aided by inertial knowledge:

1- A previously deployed orbiter, provides periodic radio direction finding (RDF) with known ephemeris and known properties of planet (spin, shape,...) and enough separation (30 to 60 degrees) between vehicles to enable triangulation.

2- Previously deployed and surveyed landmark beacons (radioisotope power source (RPS) powered on surface) across all planet. Like a grid map. Way-point navigate on/near surface. Uses direction finding to landmarks via RDF (triangulation).

3- Use of continuous visibility to GPS-like planetary infrastructure (Earth + Mars + asteroid beacons like deploying an array of micro-Sats to serve as GPS constellation)

All four provide ephemeris data over time of blimp (absolute position knowledge).

After this initial step is complete, we now need relative position knowledge among the blimp and the sondes, i.e., the blimp drops at least three anchored blimp reference beacons over local area to be explored. The blimp knows where these beacons are, and interrogates the array providing the local equivalent to inertial knowledge. The sondes use the array for local navigation in the local area. The blimp becomes the inertial reference for the sondes while the sondes need to determine range and angle to blimp. To get angle, the blimp may need to maneuver for different view angles. Autonomous Formation Flying Sensor (AFFS). transmitters and receivers are widely separated on the blimp, and are one possible candidate sensor array to carry out this function. Figure 5 summarizes the concept of local beacons assisting the navigation.

The following describes a concept for an absolute position location system using an array of orbiting micro-sats. A mobile aerobot (blimp-like) sensor platform that is capable of determining its precise location on the surface of Titan using an array of orbiting (AFF) Autonomous Formation Flying Sensors (duplex RF links that autonomously determine their relative position and bearing) with accurately known ephemerides to act as a body-centered inertial coordinate reference (Titan Centered Inertial or TCI) frame has very high mission cost-benefit value. This capability can allow the insitu aerobot to remain at, or even return to, a location of scientific interest with needed precision and to determine the precise position science data is collected. Recent efforts to define lower cost Titan exploration architectures have deleted the orbiter, making the problem of surface and atmospheric location determination and navigation even more difficult. Low cost and mass RF beacons, when deployed on Titan's surface in a location determination array, can serve as "Waypoint surface navigation references" for high resolution relative navigation or in-situ location determination. Only RF beacons are feasible due to Titan's thick hydrocarbon atmosphere that is about four times as dense as Earth's atmosphere and not penetrable by optical links.

The key to this approach, having excluded an orbiter, is to find a means of enabling absolute position determination in the TCI of the resources deployed at Titan. One proposed means assumes that the aerobot can obtain its absolute position via a direct RF link to Earth, and excludes both an orbiter and a Titan GPS. The weakness of this idea is that the aerobot can either passively drift on the strong Titan wind currents of up to 100 m/s at altitudes of 200 km or actively hold its relative position to the RF surface beacon array. In the first case, the Earth ranging/doppler signal will have poor to no sensitivity to the relatively slow aerobot drift motions normal to the RF LOS (cross range) compounded by the long propagation time (~2 hours round trip) over 10 AU. In the second case, holding fixed in relative beacon space provides insufficient information for 3-D absolute position fixing from Earth. Furthermore, the Earth to aerobot RF link viewing time is not continuous and constrains any data set and estimation methods for extracting the needed accuracy under time-varying and generally unfavorable atmospheric conditions on Titan.

The cost/mass constrained mission designs also are based on carrier spacecraft aerobraking direct entry into Titan's atmosphere and parachute deployment of aerobots and surface rovers (sondes). We propose another approach that also excludes a permanent orbiter. Instead of direct entry, the carrier spacecraft would first aerobrake around Titan once to deploy RPS-powered micro-Sat AFF Beacons in a wide arc around Titan. The ephemerides of the orbiting AFF beacons are subsequently determined by the DSN Tracking System. A second array of RPS-powered active (pulse coded) AFF RF beacons would then be deployed to Titan's surface from the aerobraking carrier using parachutes to cushion landings. These ground AFF beacons are position fixed in the absolute TCI by RF triangulation relative to the orbiting beacons, and their absolute locations are derived from data later downlinked to Earth from the aerobots. Thereby, the orbiting AFF absolute location references are transferred to the surface beacon array via DSN/navigation data analyses. In the meantime, the carrier has continued to aerobrake/deorbit into Titan's atmosphere and deploys the aerobots by parachute. To prevent crashing and creating a debris field the carrier inflates its air bags and parachutes and softly impacts Titan's surface. After the aerobots become operational, they are uplinked the orbiting AFF beacon array absolute locations in TCI. The aerobots determine their absolute position locations by RDF (radio direction finding) triangulation after acquiring the beacon pulse-coded signals. Individual beacons should have ID codes that allow the aerobot to identify its unique location.

A minimum of three RF beacons is required for position estimation in three dimensions (for a single sample estimate, or else two beacons could be sufficient with multiple estimates). Note that in the general case four beacons are required for high precision 3-D position estimation (as is the case in the global positioning system); however, location uncertainties and ambiguities may be mitigated by altimeter and other short-term precision dead-reckoning inertial sensors (gyros and accelerometers) that can be carried on the aerobot. The aerobot needs a memory of a) the uniquely identified orbiting and ground beacons, b) the locations associated with the beacons, and c) estimates for the absolute global position of the orbiting and ground network of beacons. The Aerobot and Sondes, deployed and coordinated by the Aerobot, will also use the ground AFF beacons for "Waypoint" surface navigation. Sondes will only have to perform relative navigation with respect to "waypoints" since their absolute locations will be known via their communication links with the Aerobots. The above concept enables the primary functions of the Titan Aerobot and Sonde(s) navigation capability without requiring a Titan permanent orbiter with more costly resources then the carrier spacecraft.

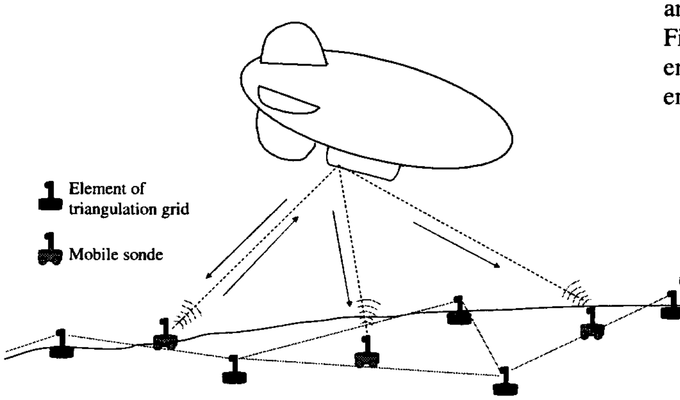

Figure 5. Blimp-Sonde Surface Navigation Scenario.

5. SONDE DESIGN

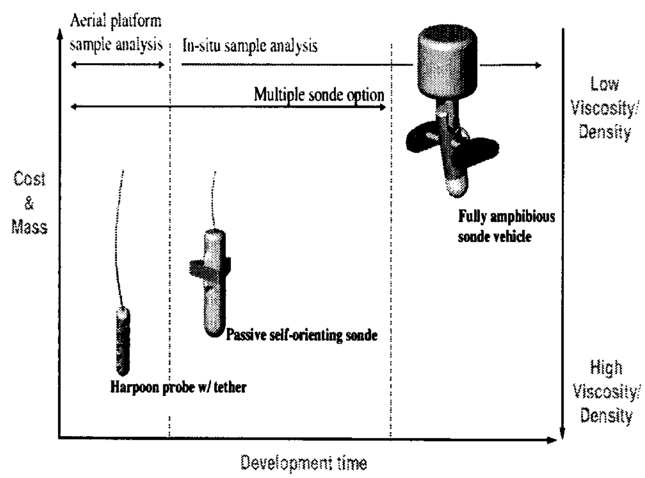

Figure 6. Sonde Design Evolution.

Figure 6 depicts the Titan sonde design evolution. The sonde design evolves from an initial harpoon tethered to the blimp, to a fully amphibious sonde vehicle capable of floating and total immersion in a liquid medium. Several options need to be considered in the design definition of the sonde. What if the terrain is definitely solid/liquid? In this case, a rigid heavy object can use conventional mobility mechanisms (float, dive, and rove). What if the terrain is definitely foamy, very porous, non-solid? In this case, a rigid object cannot move well. A solution is to deploy a tether-connected device, let the blimp drag the sampling device, and make use of appropriate end effector types: touch-and-go, or sticky-tape. What if the terrain is sticky hydrocarbon glue? In this case, a solution may be to throw-out a box inside box, then retrieve the internal box only. What if scientist wants to look deep into solid terrain? In this case, the solution is to first do a radar survey (SAR can go meters deep), then fire a penetrator, anchor the blimp, and then detach sample.

Figure 7 depicts several actuation and mobility mechanisms enabling the sonde vehicle to negotiate different kinds of environment.

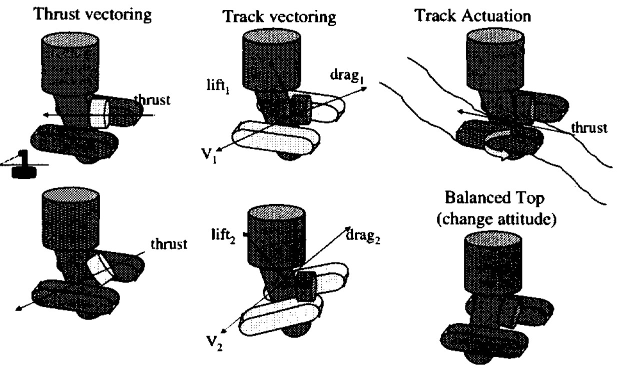

Figure 7. Sonde Actuation Mechanisms.

The elements of the Sonde Sensor Suite are: accelerometer, gyro unit, RF transmitter/receiver, long range subsonic sensor (sonar) short range ultrasonic sensor, batimeter (pressure/depth sensor), photodiode and photocell, inclinometer, odometer, thermometer, visible and infrared photographic camera.

A buoy, depicted in Figure 8, will also support the release and retrieval of several sondes. The function of the buoy is to: deploy and retrieve sondes in liquid and on the surface, being of large area and light, it can handle snow-like terrain, receive power from blimp, distribute power to sondes, maintain communication link between blimp and sondes and between sondes while submerged (act as beacon), collect samples before delivering to blimp, acts as anchoring platform for blimp on solid and liquid, instrumented to provide positioning knowledge to sondes.

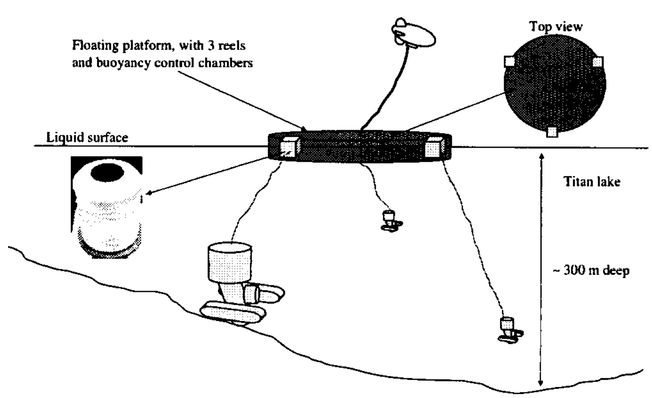

Figure 8. Buoy Functions.

The tether function is to: deploy and retrieve sondes in liquid and on the surface, receive power from blimp, distribute power to sondes, maintain communication link between blimp and sondes and between sondes while submerged, act as anchoring mechanism for blimp on solid and liquid.

6. HERD COOPERATION CONTROL

Several experiments in assessing the performance of the system have been carried out, with the objective of: 1) demonstrating the feasibility of herd navigation during Direct to Earth communication link (simulating reference maneuver); 2) demonstrating the behavior of sondes in heterogeneous environments (terrain, sludge, liquid); 3) verifying that a distributed computation (one CPU on board each vehicle) environment is best suited to this purpose. The output of these experiments are: power requirements for blimp and sondes in different scenarios, performance evaluation of estimation architectures in those scenarios, comparison of results with idealized case (no wind, flat terrain, no environment).

Figure 9 shows the conceptual image-based guidance and control algorithm for the Titan herd. A potential field controller, described next, is used to command the herd's position around obstacles to the target. Images from an orbiter, or images taken by the blimp, are used to extract features of the interesting area which have scientific interest. A digitization of the pictures converts them into a series of allowable or forbidden points, from which a field of potentials can be automatically reconstructed. This is done by the CPU inside the blimp. Knowing the current inertial position of the blimp and sondes in a Titan centered frame, the herd's configuration is monitored, as well as the network of communication links between the members of the herd, including the blimp. This monitoring is necessary for failure tolerance strategies and hazard avoidance.

There has been a large body of work on motion planning and cooperative control of many robots. Our goal is to plan and control a number of sondes and blimp's motion from the initial positions to a moving or stationary target in a desired manner while avoiding possibly moving obstacles. To achieve this goal, we selected the potential field method for its simplicity and its low computational requirements. There are a number of variations on the potential field method [2], [3], [4]. One of the variations, virtual force field (VFF)[5], works best for real-time applications, and it's suited for the limited computational resources available on the sondes.

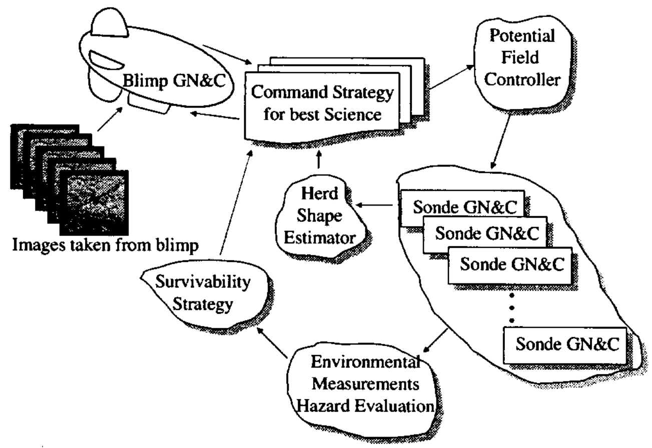

Figure 9. Conceptual Image-based Guidance & Control of Titan's herd.

The VFF method uses attractive and repulsive potentials to generate actuator forces that smoothly drive the vehicle to a specified target while avoiding obstacles. The sondes and other obstacles can be represented as point particles on a Euclidean space at a fixed time. For each point particle *j* surrounding any given sonde *i*, a virtual force is asserted from particle *j* to sonde *i*. This virtual force has the form

$$F_{i,j}(X_i, X_j) = \frac{c_{i,j}(X_j - X_i)}{\left(r_{ij}\right)^{n+1}} \tag{1}$$

where X is the position of the particle. $r_{ij} = \left\|X_i - X_j\right\|$ is the Euclidean distance between point particle i and j, n is a user-defined constant determining the strength of the field, and $c_{i,j}$ is the coefficient for the force vector. $c_{i,j}$ can be positive if the force is attractive and negative if the force is repulsive. To ensure that the sondes do not collide with each other and other obstacles, each sonde is asserted with repulsive forces (negative $c_{i,j}$) from stationary obstacles and other moving obstacles, including neighboring sondes. Targets assert attractive forces (positive $c_{i,j}$) to guide the sondes toward the targets. The sondes can also assert attractive forces to each other when they are too far part and assert repulsive forces when they are too close to each other. This has the effect of keeping the sondes moving in a formation while avoiding colliding to each other. The overall virtual force applied by the entire system on the i-th sonde is, therefore,

$$F_i = \sum_{j \neq i} F_{i,j}(X_i, X_j) \tag{2}$$

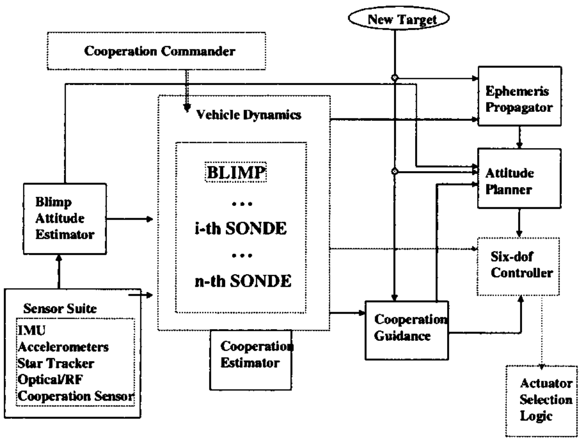

Figure 10. Blimp-Sonde Control Functional Simulation Diagram.

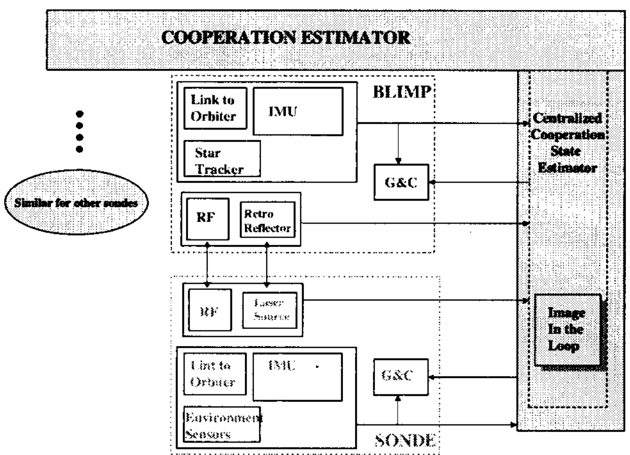

Figure 11. Conceptual flow of information from sensors to Cooperation Estimator.

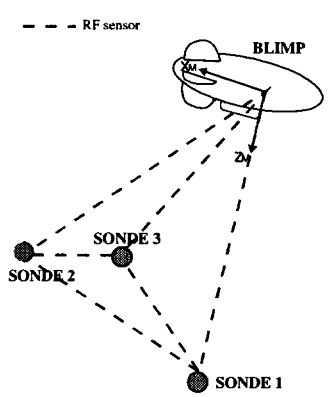

Figure 12. Sonde-Blimp Intra-herd Distributed Communication Plan.

Figure 10 shows a functional diagram of the simulation at a conceptual level. After Commands are given to the sondes by the blimp, the controller is activated. The Controller is split into the control of the separated sondes in the form of attitude and position control forces and torques, and in potential field (cooperation) controller. The control inputs are filtered by the dynamics and noise models of the actuators. The noisy control inputs are then used in the Dynamics module, which propagates the state of the entire herd, and in addition provides updates of the inertial state and of the environmental perturbations acting on the system. The dynamic state is subsequently manipulated by the Sensor Models, which reproduce sensor measurements with noise (Star Tracker, Accelerometers, Gyros, and Laser and Radio Frequency-based metrology). With the measurements available, the cooperation estimator can now provide estimates of the relative herd state, which is then delivered to the Commander to close the cycle. The Sensor models and Estimators, including the Cooperation Estimator, run in discrete time, whereas the Commander, Controller, and Dynamics modules run in continuous time, making this simulation a hybrid discrete-continuous simulation. Figure 11 shows the essential elements of the cooperation estimator, which uses a generalized version of the network depicted in Figure 12 to process intra-herd variables for purposes of estimating the current relative state of the entire herd of vehicles. Figure 11 shows the flow of sensor data into the cooperation estimator, supported by the image-in-the-loop-architecture summarized in Figure 9. The extension to more than three sondes is not easy, as the estimator architecture becomes dependent on the number of communication links. The distributed relative sensing element is based on Cooperation Sensor Ka-Band Transceivers/Patch Antennas, which provides range and bearing and full-duplex links between: blimp and sonde, and sonde to sonde [1]. Additional links can be added for fault protection and collision avoidance. [5] and [6] contain a summary of the equations used in the dynamics and control simulation model of the sondes.

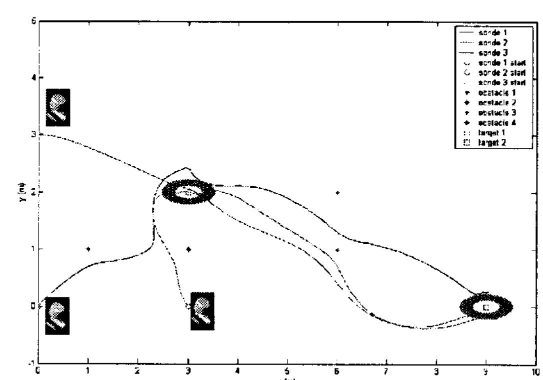

Figure 13.Trajectory of sondes reaching targets after negotiating two sets of obstacles.

Figure 13 shows the relatively smooth trajectory of three sondes reaching targets after negotiating two sets of obstacles. Figure 14 and 15 show, respectively, the sonde relative trajectory and power demand to cover the ground shown in Figure 13.

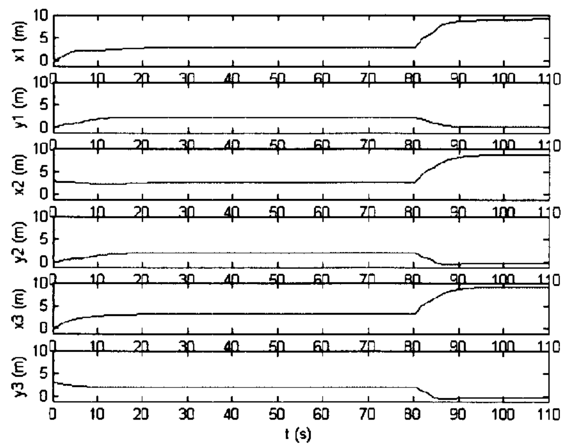

Figure 14.Sonde position as a function of time.

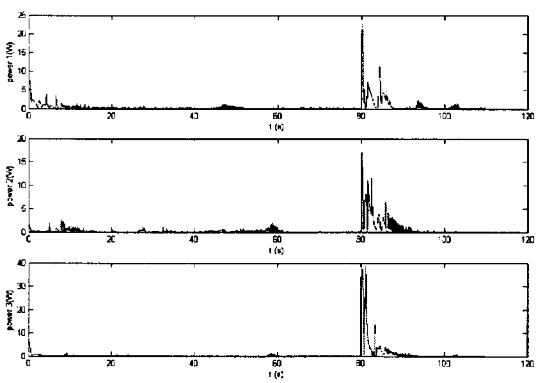

Figure 15.Power to drive sondes as a function of time.

7. SURVIVABILITY AND FAULT TOLERANCE

Based on mission concepts and architecture, a study was conducted to investigate failure modes of different mission components to include interactions between different failures and their effects on mission objective and performance. The mechanism for surviving against failures include: survivability against low temperature, survivability against other environmental factors, like atmospheric deposit, corrosion etc, survivability against hardware/software failure, and others. These include mitigation methods such as: fault diagnosis, reconfiguration, and recovery with degraded performance. Figure 16 and 17 show failure modes and survivability options for the blimp and sondes, respectively. The columns in Figures 16 and 17 identify the main components on each subsystem which are subject to failure, the failure modes and their effects on the system and on each subsystem, and a list of recovery and preventive actions to alleviate those failure modes. Because of the cooperation paradigm being used to guide and control the herd, almost all the failure modes in Figures 16 and 17 can occur. Hence, the survivability aspect of the mission must be dealt with in the early phases of the design.

	SubSystems	Components	Failure modes	Effect on subsystem	Effect on system	Recovery action	Preventive action
Blimp	Body	Material	Unknown at 90°K				
	ACS	Sun-sensor	Unknown at 90°K				Replication
	Buoyncy cntrl	Ballonette	Material for low temp	Loss of stability - pointing problem	Comm loss if direct comm to earth - data rate loss w orb		
		Pumps	Sealant and bearing failure for extreme low temp				Cryogenic lubricant, sealant usage
		Plumbing					
	Comm	Phased arr ant to earth	Low temp for the comm electronics and other electronic failures	Comm break to earth			Comm electronics needs to be warm env in blimp
		Ant - talking to orbiter		Comm break to orbiter		Switching bet multiple trans/recv	
		Link to sondes		Comm break to sondes		Switching bet multiple trans/recv	
	Temp cntrl	Heaters					
	Instruments	GC/MS	Unknown at 90°K	Loss of science data			warm encl
		NMR					
	CD&H	Computer	Unknown at 90°K - typical computer system failures if in warm enclosure	Loss of science data	Loss of science data	Fault detection and diagnosis through testing and task migration	warm encl
		Memory					
		Bus Interf					
		Comm Interf					
	Power	RTG					
		Battery	Lose power quickly - should be rechargeable				Use rechargeable battery

Figure 16. Blimp Failure Modes and Survivability Options.

8. CONCLUSIONS

We have proposed a novel paradigm to enable cooperative behavior of a group of data gathering vehicles moving in an unknown environment. Challenges have emerged in the area of position knowledge, distributed computing, evolvable architectures. Feasibility has been demonstrated using a potential fields approach for commanding the herd. The sequence of Delivery Phases delineates the complexity of this delivery. Integrated blimp, sondes and cooperation system simulation architectures have been proposed that enable realistic designs and performance metric quantification. A Titan-based GPS-like environment has been proposed to provide a robust direct-to-Earth communication link, as well as for inertial position knowledge of the surface system.

	SubSystems	Components	Failure modes	Effect on subsystem	Effect on system	Recovery action	Preventive action
Sondes	Mobility cntrl	Sonar Sensors	Sensor failure or failure of sensor data processing	Wrong clearance and depth estimate	Might get stuck - need to avoid	with close sondes and wireless link, info from others	Cryogenic lubricant, sealant usage
		Propellers/ flippers	Mechanical failure	Mobility loss - may be usable sensors	Mobility loss - may be usable sensors	Towing by other sondes	
		motors/ actuators	Mechanical failure loss of power	Mobility loss - may be usable sensors	Mobility loss - may be usable sensors	Towing by other sondes	
	Instr/Camera	GC/MS	Unknown at 90°K	Loss of science data			warm enclosure
		NMR					
		Camera					
	CD&H	Computer	Unknown at 90°K - typical computer system failures if in warm enclosure	Loss of science data	Loss of science data	Fault detection and diagnosis through testing and task migration	warm enclosure
		Memory					
		Bus Interf					
		Comm Interf					
		Instrument Interfaces					
	Comm Sys	Wireless to Blimp	Loss of range - improper alignmnt for directed ant	Loss of sonde data		sonde unusable with no other alternate link	Ominidirectional - needs more power
		Wired link to Blimp					
		Fiber link to Blimp	Fiber cut - end electr need to be in warm envimoment	Loss of sonde data		sonde unusable with no other alternate link	fiber stiffening mechanism
		Wireless link to other sondes	Other sondes out of range	loss of data from failed sonde	Partial loss of data	Random moving around if loss of range	
	Power	Battery	Lose power quickly - should be rechargeable	Loss of sonde data			Use rechargeable battery
		RTG	Unknown at 90°K				
		Pwr convrts	Unknown at 90°K				Warm enclosure - with heat insulation
	sample	TBD Sensors	Mostly mechanism failure because of low temp	With replication, loss of mission time - without replication, loss of science data			Replication of sampling handling in other sondes

Figure 17. Sondes Failure Modes and Survivability Options.

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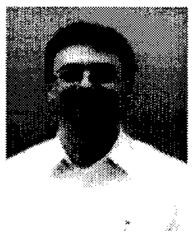

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